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Numerical implementation for fatigue assessment of butt joint improved by high frequency mechanical impact treatment: A structural hot spot stress approach

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ABSTRACT

In the study, three-dimensional finite element modelling of high frequency mechanical impact (HFMI) treatment is presented for butt joints of four strength grade materials (Q235B, AISI 1006, 45 Steel and AISI 2205). The fatigue assessment of butt joints by HFMI is implemented by structural hot spot stress approaches, i.e., linear surface extrapolation (LSE) and through thickness at the weld toe (TTWT). The effective structural hot spot stress concentration factors for HFMI-treated joints are determined, and the dependence of HFMI improvement on material strength and external stress is well captured by TTWT method. Following structural hot spot stress S-N curves for as-welded joints recommended by IIW, the structural hot spot stress S-N curves for HFMI-treated joints are suggested if the slope m of S-N curves for HFMI-treated joints is designated to vary from 5 to 10, inversely proportional to material strength. At final, the characteristic fatigue strength (FAT) has been determined and verified with the available experimental data.

1. Introduction

Welded structures are vulnerable to fatigue even though welded joint is well qualified. Weld toe region tends to be fatigue crack initiation site due to local stress concentration caused by weld reinforcement and defect. The guideline by the International Institute of Welding (IIW) recommends several post-weld treatment methods of weld toe to improve the fatigue resistance for steel and aluminum structures, including burr-grinding, TIG remelting (i.e. TIG dressing), hammer peening and needle peening [1]. As to these techniques, two benefit mechanisms can be identified: (a) reducing the local stress concentration by achieving a smooth transition between the plate and the weld face (burr-grinding and TIG dressing et al.); (b) eliminating the high tensile residual stress by inducing compressive residual stresses at the weld toe (hammer peening and needle peening et al.) [2–5]. Alternatively, extensive experiments have validated that the improvement of weld toe fatigue can be effectively achieved by high frequency mechanical impact (HFMI) treatment, including ultrasonic impact treatment (UIT) [6,7], ultrasonic peening (UP) [8], ultrasonic peening treatment (UPT) [9,10], pneumatic impact treatment (PIT) [11] and ultrasonic needle peening (UNP) [12]. High frequency mechanical impact between indenters and material gives rise to severely plastic deformation at weld toe region, resulting in high compressive residual stress as well as better transition radius at weld toe, which is responsible for the improvement of fatigue strength after HFMI treatment [13,14].

Numbers of fatigue tests for different steels indicate that fatigue performances of welded joints after HFMI treatment are quite different from the as-welded ones in terms of FAT value and the slope of S-N curve [4,15–17]. The IIW recommendation for the post-weld improvement by hammer peening or needle peening suggests the fatigue strength increases in allowable stress range by a factor of 1.3 for lower strength steel in contrast with a factor of 1.5 for higher strength steel [18]. Comparison in fatigue design between as-welded and HFMI-treated joints for three kinds of strength grade steels were performed by Wang et al. [16], and their results indicated that: (a) The degree of improvement for post-weld treated components depends on material strength; (b) The slope of median S-N curves of HFMI-treated joints are much larger than that of as-welded ones, and $m = 10$ is recommended for fatigue design of HFMI-treated joints; (c) The characteristic fatigue strength of joint by HFMI treatment is not independent of average stress any more, and relation between characteristic fatigue

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strength and stress ratio was also suggested. Yildirim and Marquis [19] recently reviewed the published experimental data on the fatigue strength of welded joints improved by HFMI methods, and proposed that an S-N slope of $m = 5$ could be used to estimate the fatigue life, and the degree of improvement for post-weld treated components should be modified by taking material strength into account. Accordingly, it can be concluded that fatigue performances of welded joints improved by HFMI treatment significantly depend on material strength and applied stress range, i.e. the degree of improvement decreases as material strength decreases or the maximum applied stress increases.

Although noticeable progress on fatigue assessment of welded joints improved by post-weld treatment methods has been achieved, systematic investigation for different strength steels, aluminum alloys, titanium alloys is still under development. In the study, numerical simulation is employed to study the elastic–plastic dynamic process of HFMI treatment on weld toe of butt joints, and four kinds of steels with different strength grades are considered. During the modelling, the localized plastic deformation is generated by impact between the needles and weld toe, which produces a field of compressive residual stress and reliefs the stress concentration at weld toe simultaneously. Furthermore, referred to IIW Recommendation [1], the fatigue improvement by HFMI treatment is assessed by structural hot spot stress approaches, i.e., linear surface extrapolation [20] and through thickness at the weld toe [21], and the comparison between them is also given.

2. Overview of structural hot spot stress approaches

According to IIW recommendation [18], the effect of several post-weld treatment methods of weld toe to improve the fatigue resistance for steel structure can be evaluated in terms of nominal applied stress range or local approaches (structural hot spot stress and notch stress). In nominal stress approach, different weld details are assigned with characteristic fatigue strength values largely based on laboratory testing, and the similar weld details are specified to same fatigue strength regardless of the actual dimensional variations of a particular structural detail and material strength. Moreover, practical structures are often so geometrically complex that the determination of the nominal stress is cumbersome or impossible. In contrast, the structural hot spot stress approach avoids the previously noted difficulties associated with applying the nominal stress approach, and is computationally less demanding than fracture mechanics methods. Structural hot spot stress takes into consideration the dimensions and stress concentrating effects of the detail at the anticipated crack initiation site while excluding the local non-linear stress peak caused by the notch at the weld toe. Therefore, there is growing interest in the structural hot spot stress for welded joint assessment [22]. It is worth noting that Yildirim et al. [23] recently reevaluated the published data for welded joints improved by HFMI treatment by the structural hot spot stress, and concluded that the characteristic fatigue strength curves as functions of yield strength. In the study, two classical methods for determining the structural hot spot stress for fatigue analysis of welded structures are adopted to evaluate the improvement of the fatigue resistance by HFMI, that is, linear surface extrapolation (LSE) [20] and through thickness at the weld toe (TTWT) [21]. Dong [24,25] and Xiao and Yamada [26,27] have proposed alternative approaches to determine the structural stress which are beyond the scope of the present study.

2.1. Linear surface extrapolation (LSE)

The IIW recommendations for determining the structural hot spot stress of as-welded joint are based on the principal of surface extrapolation. Niemi [28,29] has proposed distances of 0.4 and 1.0 times plate thickness, t, from the weld toe as shown in Fig. 1. The extrapolation expression is given as follow:

$$\sigma_{hs} = 1.07\sigma_{0.4t} - 0.67\sigma_t \quad (1)$$

2.2. Through thickness at the weld toe (TTWT)

Radaj [30] suggested that structural hot spot stress could be evaluated alternatively by linearization through the wall thickness, which can determine the structural hot spot stress at some location in a fabricated structure without the nonlinear stress peak due the weld itself. As shown in Fig. 2, the nonlinear stress distribution along the thickness direction is assumed to be monotonic with the peak stress (notch stress) occurring at the weld toe. The notch stress (σ_{loc}) can be divided into three parts: membrane stress (σ_m), bend stress (σ_b) and nonlinear stress peak (σ_{lnp}). The structural hot spot stress is derived from the notch stress, which only contains membrane stress and bending stress. In the numerical simulation, the through-thickness stress distribution ($\sigma_x(y)$) can be obtained from a finite element model. A simple structural hot spot stress distribution shown as the dotted line in Fig. 2 can be set up. The simple structural hot spot stress distribution in form of membrane stress and bending stress are equilibrium-equivalent to the through-thickness stress distribution. The membrane stress (σ_m) and bend stress (σ_b) can be calculated by Eqs. (2) and (3), and the structural hot spot stress (σ_{hs}) calculated by Eq. (4) is the sum of σ_m and σ_b.

$$\sigma_m = \frac{1}{t}\int_0^t \sigma_x(y)dy \quad (2)$$

$$\sigma_b = \frac{6}{t^2}\int_0^t \sigma_x(y)\left(\frac{t}{2} - x\right)dy \quad (3)$$

$$\sigma_{hs} = \sigma_m + \sigma_b \quad (4)$$

It should be noted that the distribution of the through-thickness stress should be monotonically increasing or decreasing while using the above method to calculate σ_m and σ_b [31]. In the present study, the through-thickness stress is not monotonous distribution, as a result, only the monotonous part near the weld toe was chosen for calculation.

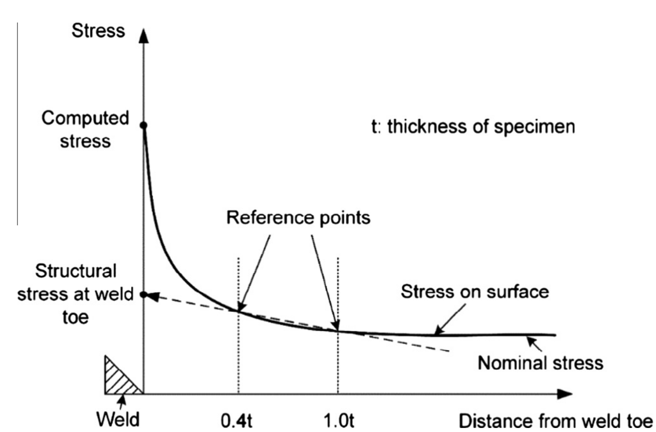

Fig. 1. Definition of structural spot hot stress.